TRANSVERSE VOLUME EMF AND STRETCHING OF DIFFUSION LENGTHS IN MULTIVALLEY SEMICONDUCTORS

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In a multivalley semiconductor, an electric field E_x gives rise to transverse currents of electrons belonging to different valleys

$$j_y^{(\alpha)} = -\mu_{yx}^{(\alpha)} n^{(\alpha)} E_x \qquad (1)$$

($\mu_{ik}^{(\alpha)}$ - mobility tensor in α-th valley). If the semiconductor is homogeneous in the y direction then $n^{(\alpha)} = n/m$ everywhere except in a thin surface region (n - total electron density, m - number of equivalent valleys), so that in a crystal with cubic symmetry

$$\sum_{\alpha=1}^{m} \mu_{yx}^{(\alpha)} = 0$$

the current in the y direction equals 0. In the presence of a gradient dn/dy, the continuity of the current $j_y^{(\alpha)}$ is violated, leading to the appearance of an intervalley redistribution

$$n^{(\alpha)} - \frac{n}{m} = -\tau \frac{dj_y^{(\alpha)}}{dy} \cong \mu_{yx}^{(\alpha)} \tau \frac{E_x}{m} \frac{dn}{dy}, \qquad (2)$$

where τ is the intervalley relaxation time. Deviation from the intervalley equilibrium (2) gives rise to anisotropy of the conductivity of the semiconductor, so that the total electron current in the y direction now consists of the diffusion current, connected with the gradient dn/dy, the drift current in the field E_y, and the anisotropic current in the field E_x. Since the latter is proportional to the dn/dy, a change takes place in the effective coefficient of diffusion in the y direction

$$j_y = -D_n^* \frac{dn}{dy} - \mu_n n E_y, \qquad (3)$$

where

$$D_n^* = D_n(1+\gamma^2), \qquad (4)$$

$D_n = (kT/e)\mu_n$ is the average (isotropic) electron mobility, and γ is the dimensionless electric field E_x:

$$\gamma^2 = \frac{1}{m}\sum_{\alpha=1}^{m}\left(\frac{\mu_{yx}^{(\alpha)}}{D_n} E_x L\right)^2, \quad L = \sqrt{D_n \tau}. \qquad (5)$$

Formulas (3) - (5) were obtained assuming a small redistribution, meaning smooth inhomogeneity

$$\gamma L << L_p, \qquad (6)$$

where L_p is the characteristic length of the inhomogeneity. We note that in the opposite case - near a sharp inhomogeneity - phenomena similar to those considered in [1, 2] come into play.

We now derive some of the consequences of the growth of the diffusion coefficient.

1. Monopolar Semiconductor

In this case the carrier-concentration gradient can be obtained by homogeneous doping. The condition that there be no transverse current ($j_y = 0$) leads to the appearance of a transverse volume emf

$$V_y = -\int_{y_1}^{y_2} E_y dy - \frac{kT}{e} \ln \frac{n_2}{n_1} = \gamma^2 \frac{kT}{e} \ln \frac{n_2}{n_1}. \quad (7)$$

The emf V_y is strictly proportional to the square of E_x; its sign is determined by the sign of the concentration gradient, and its magnitude is proportional to τ (and can apparently be used for its measurement).

In the derivation of formula (7) it was assumed that τ does not depend on y. At low temperatures and high impurity concentrations (see [3, 4]), τ depends on the concentration and on the degree of donor ionization. In the simplest case, when all the donors are ionized and quasineutrality takes place, it can be assumed that $\tau = (a + bn)^{-1}$; then

$$V_y = \gamma_0^2 \frac{kT}{e} \ln \left[\left(\frac{n_2}{n_1} \right) \left(\frac{a + bn_1}{a + bn_2} \right) \right], \quad (8)$$

where γ_0 is the value of γ at $\tau = a^{-1}$.

2. Bipolar Nonequilibrium Semiconductor

The inhomogeneous distribution of the electrons in the semiconductor can be produced by photogeneration that is inhomogeneous in the y direction (or else by homogeneous generation but as a result of the influence of surface recombination). The coefficient of bipolar diffusion in the y direction is then equal to

$$D = \frac{D_p (D_n^* p + D_n n)}{D_n n + D_p p}, \quad (9)$$

i.e., it remains equal to D_p in an n-type semiconductor and becomes equal to D_n^* in a p-type semiconductor. When $p \approx n$ we get

$$D = 2D_p D_n / (D_p + D_n) [1 + (\gamma^2/2)] .$$

The growth of the diffusion coefficient in the y direction with increasing field E_x leads to a "stretching" of the diffusion lengths of the carriers with respect to recombination

$$\left. \begin{aligned} L_p &= L_p^0 (1 + \gamma^2)^{1/2} \text{ for } p \gg n, \\ L_p &= L_p^0 [1 + (\gamma^2/2)]^{1/2} \text{ for } p \approx n, \end{aligned} \right\} \quad (10)$$

(We note that the criterion (6) is always satisfied here if $L_p^0 \gg L$, which is usually the case by a large margin).

The dependence L_p on the drawing field E_x greatly influences the field dependence of the photocurrent (cf., e.g., [5]).

In conclusion we note that inasmuch as in germanium the length of the intervalley scattering L remains essentially larger than the cooling length in almost all situations (the only exception being cases of very high densities and extremely low temperatures, the condition $\gamma > 1$, which is necessary for an appreciable stretching of L_p, is still satisfied in non-heating fields. However, at low temperatures, the intervalley scattering time τ, determined by the scattering with emission of intervalley phonons, may turn out to be sensitive to small degrees of heating, so that in general $\tau = \tau(E_x)$. Finally, in the bipolar case, the intervalley scattering may proceed via an intermediate exciton state (similar to the proposed intervalley scattering via a bound state by donors in [3, 4]). Then τ will depend on p and will depend on y, together with the concentration, at high illumination levels ($p \approx n$).

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